DEVELOPMENT AND APPLICATION OF SWAT TO LANDSCAPES WITH TILES AND POTHOLES

B. Du, J. G. Arnold, A. Saleh, D. B. Jaynes

ABSTRACT. SWAT (Soil and Water Assessment Tool) is a watershed model that has been incorporated into USEPA's modeling framework called BASINS used for total maximum daily load (TMDL) analysis. It is thus important that SWAT realistically simulate tile flow and pothole landscapes that are common in much of the Corn Belt and Great Lakes states. In this study, SWAT was modified to simulate water table dynamics and linked with a simple tile flow equation. Algorithms were also added to SWAT to include simulation of potholes (closed depressions), surface tile inlets, and aeration stress on plants. Flow interaction between HRUs was introduced in order to simulate pothole water. The modified SWAT model (SWAT-M) was evaluated using eight years of measured flow data from Walnut Creek watershed (WCW), an intensively tile-drained watershed in central Iowa. The model was calibrated during the period of 1992 to 1995 and validated during the period of 1996 to 1999. In addition, comparisons between the enhanced version (SWAT-M) and older version (SWAT2000) of SWAT were conducted. For assessing overall performance of the SWAT models, predictions were compared to data measured at stream sites approximately at the midpoint of the watershed (site 310) and at the outlet (site 330). Nash-Sutcliffe E values for the simulated monthly flows during the calibration/validation periods were 0.88/0.82 and 0.84/0.72 at sites 310 and 330, respectively. The relative mean errors (RME) of the simulated monthly flows during the calibration/validation periods were -2%/-1% and -18%/10%, respectively, for the same two sites. These statistical values indicate that SWAT-M estimated both pattern and amount of the monthly flows reasonably well for the large flat landscape of WCW containing tile drains and potholes. SWAT-M needs to improve in its daily prediction because of its lower E values (-0.11 to 0.55), compared to the monthly results. In applying the model to a third site (site 210) that was predominantly influenced by tile drainage, it was concluded that the pattern and amount of simulated monthly subsurface flows (E values of 0.61 and 0.70 and RME values of 10% and -9% for the calibration and validation periods, respectively) were relatively close to the measured values. Nevertheless, SWAT-M simulation of daily subsurface flows was less accurate than monthly results. In general, the pattern and amount of monthly flow and subsurface tile drainage predicted by SWAT-M has been greatly improved as compared to SWAT2000.

Keywords. Modeling, Pothole, Subsurface flow, SWAT, Tile drainage, Water quality, Watershed.

pproximately 25% of our nation's cropland (over 40 million ha) requires improved drainage for agricultural production (Pavelis, 1987). Artificial drainage is needed on over 50% of the cropland in some states (Skaggs et al., 1992). Much of the Corn Belt from Ohio to Iowa and the Great Lakes states were once swamps and wetlands that were drained to become some of the most productive land in the world. Artificial or improved drainage is necessary to produce crops on these lands using modern production practices. Agricultural drainage systems not only provide a better environment to increase crop yields, but also improve field conditions for timely tillage, planting,

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Research supported in part by USDA-NRICP grant #2000-00918. The authors are **Bing Du**, Senior Research Associate, and **Ali Saleh**, Research Scientist, Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas; **Jeff G. Arnold, ASAE Member**, Hydraulic Engineer, USDA-ARS, Temple, Texas; and **Dan B. Jaynes**, **ASAE Member**, Soil Scientist, USDA-ARS National Soil Tilth Laboratory, Ames, Iowa. **Corresponding author:** Bing Du, Texas Institute for Applied Environmental Research, Tarleton State University, P.O. Box T-0410, Stephenville, TX 76401; phone: 254-968-9574; fax: 254-968-9790; e-mail: bdu@tiaer.tarleton.edu.

and harvesting in these poorly drained soils, which have improved agricultural production on nearly one-fifth of U.S. soils (Skaggs et al., 1994). During the last 80 to 90 years, subsurface tile drainage systems, coupled with the increase in fertilizer and pesticide applications, have created environmental concerns in both surface and groundwater supplies (Baker and Johnson, 1981; Cambardella et al., 1999). Some of the highest contributions of nitrogen in surface waters come from fields with subsurface drains (Gilliam et al., 1999). Many of the impaired waters in the Midwest are in agricultural watersheds. Another concern is excess nitrogen from agricultural sources in primarily the Upper Mississippi River Basin, which is suggested as a contributing cause of hypoxia in the Gulf of Mexico (Rabalais et al., 1996). Because subsurface drainage systems are installed on farm fields, they profoundly affect watershed hydrology (Hewes and Frandson, 1952; Eidem et al., 1999; Jaynes et al., 1999). Another natural feature in the Midwest Corn Belt area is prairie potholes or enclosed shallow depressions, which periodically flood and delay water movement out of the watershed (Eidem et al., 1999; Jaynes et al., 1999). This prolonged wetness causes stress to crop growth because saturated soils do not provide sufficient aeration for crop root development. Cropping systems in pothole regions employing tile drainage systems have unique hydrologic and nitrogen transport

characteristics (Eidem et al., 1999; Jaynes et al., 1999). Therefore, to accurately model water and agrochemical fate and transport in tile-drained soils, it is necessary to develop models capable of simulating landscapes with both tile drainage and pothole physiography.

Several models have been developed to simulate subsurface drainage. Analytical solutions for steady-state flow in homogeneous soil underlain by an impermeable layer were first developed by Kirkham (1958). Duffy et al. (1975) developed mathematical models of flow and chemical processes in tiled fields. Skaggs (1978) was the first to develop a comprehensive computer model (DRAINMOD) to simulate the water balance and the impact of subsurface water management of tile-drained fields. DRAINMOD is a widely used and accepted drainage model, and several of its components are used by other field-scale models. DRAIN-MOD has been linked to the CREAMS models (Knisel, 1980) by passing hydrologic variables to CREAMS for erosion and chemical transport (Parsons and Skaggs, 1988). The Root Zone Water Quality Model (RZWQM) was also modified to simulate tile flow using DRAINMOD tile flow equations (Singh and Kanwar, 1995). The GLEAMS model (Leonard et al., 1987) was modified to simulate subsurface drainage and shallow water table fluctuations (Reyes et al., 1993; Reyes et al., 1994). A tile drain component was added to the EPIC model (Williams et al., 1984) using a user-specified drawdown time equation (Chung et al., 2002) that replaces the DRAINMOD equation. The EPIC equation assumes that the tile system has been designed for a certain water table drawdown time, typically 24 to 48 h to avoid excess plant stress. Except for the above field-scale models, six watershed-scale models have been developed using DRAIN-MOD to describe field-scale processes and linked with various methods to describe the transport and fate of flow, nutrients, and pesticides as the drainage water moves through the canal and stream network (Skaggs et al., 2003). Differences among these six models are in how the models simulate flow and water quality in the canals and streams (Amayata et al., 2004; Fernandez et al., 2001, 2002; Fernandez et al., 2005, 2003; Amayata et al., 2001).

In this study, a watershed-scale model called SWAT (Soil and Water Assessment Tool) was modified to simulate water table fluctuations, tile flow, and pothole topography (Arnold et al., 1998). SWAT is a conceptual, continuous-time model that was developed in the early 1990s to help water resource managers in assessing the impact of management and climate on water supplies and nonpoint-source pollution in watersheds and large river basins. In SWAT, large watersheds are typically divided into smaller subwatersheds based on topography to accommodate channel and reservoir routing. The subwatersheds can be further subdivided into hydrologic response units (HRUs). HRUs in each subwatershed are created by overlaying soils and land use and "lumping" similar soils and land use combinations. Model components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing, and pond/reservoir routing. The latest version (Neitsch et al., 2002a; Neitsch et al., 2002b) has several significant enhancements that include: bacteria transport routines; urban routines; the Green-Ampt infiltration equation; an improved weather generator; the ability to read in daily solar radiation, relative humidity, wind speed, and potential ET; Muskingum channel routing; and modified

dormancy calculations for tropical areas. SWAT has been incorporated in USEPA's modeling framework called BA-SINS used for total maximum daily load (TMDL) analysis. It is thus critical that SWAT realistically simulate the tile flow and pothole topography that is common in much of the Corn Belt and Great Lakes states.

The first objective of this study was to modify SWAT to simulate surface and subsurface flow for landscapes with tile drainage systems and pothole topography. The second objective was to evaluate the enhanced SWAT model (SWAT-M) with new tile drainage and pothole surface storage components, using measured data from the Walnut Creek watershed (WCW) in central Iowa, and compare the older version of SWAT (SWAT2000) to SWAT-M to further determine the effect of the new enhancements on predictions.

MODEL DEVELOPMENT

SWAT2000 was enhanced with a subsurface tile flow component and tested with data from a field-scale area with satisfactory results (Arnold et al., 1999). However, it was found that SWAT2000 was not able to accurately simulate subsurface flow and stream discharge when applied to a watershed-scale basin because the old tile drain algorithms were not working properly and the effects of potholes on the surface hydrology had not been included (Arnold et al., 1999).

SOIL WATER ROUTING

The soil water routing was modified from SWAT2000 to SWAT-M to include prediction of water table depth. This was accomplished by:

- Setting a restrictive soil layer (low saturated conductivity) at the bottom of the soil profile. The restrictive layer simulates a confining layer or a maximum water table depth.
- Allowing the soil profile above the restrictive layer to fill to field capacity. After the bottom soil layer reaches field capacity, additional water is allowed to fill the profile from the bottom soil layer upward. Then the height of the water table (above the impermeable layer) is calculated.

Total porosity (*por*) is calculated from bulk density (*bd*) assuming a particle density of 2.65 Mg m⁻³ (*por* = 1 – bd/2.65). It is assumed that a fraction of the porosity is filled with air (v_{air}) and the soil pores do not fill to total porosity with water. If soil water (sw) exceeds saturation in a layer, excess water stays in the layer immediately above the saturated layer. A layer is saturated (before total porosity is reached) when water fills all pores except those filled with air:

$$sat_l = fc_l + (por_l - fc_l) * v_{air}$$
 (1)

where sat_l is soil water saturation in soil layer l (subscript l indicates the soil layer l), fc_l is the field capacity, por_l is the soil porosity, and v_{air} is the pore volume filled with air. When soil water in a layer immediately above a saturated layer does not exceed saturation, a water table is calculated in that layer:

$$wt_l = \frac{sw_l - fc_l}{(por_l - fc_l) * v_{air}}$$
 (2)

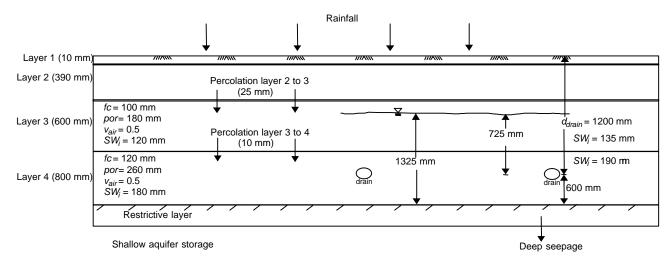


Figure 1. Diagram showing an example water table calculation after a rainfall event.

where wt_l is the height of the water table above the bottom of soil layer l, and sw_l is the soil water content.

Figure 1 illustrates an example calculation of the water table rising into layer 3. At the start of the day, assume that the soil water contents of layers 3 and 4 are 120 and 180 mm, respectively. Based on the soil water routing equation used in SWAT (using conductivity and layer thickness), 25 mm percolated from layer 2 into 3, and 15 mm could percolate into layer 4. Soil water in layer 4 is 180 + 15 = 195 mm, which exceeds saturation (190 mm using eq. 1). Since only 10 mm of storage is available in layer 4, 5 mm remains in layer 3, giving final soil water in layer 3 of 135 mm. This is below total saturation (140 mm using eq. 1); thus, equation 2 is used to compute water table height above the bottom of layer 3, which is added to the depth of layer 4 to determine the water table height above the impermeable layer:

$$800 + \left[\frac{135 - 100}{(180 - 100) * 0.5} \right] * 600 = 1325 \text{ mm}$$

Assuming the tile depth from the surface is 1200 mm and the total soil depth above the impermeable layer is 1800 mm, the water table height above the tiles is 725 mm.

TILE FLOW EQUATION

When the water table height exceeds the height of the tile drains, tile flow occurs. The amount of flow is calculated with the equation (Arnold et al., 1999):

$$tile_{wtr} = (h_{wt} - h_{tile}) * \left(1 - \exp\left[\frac{-24}{t_{drain}}\right]\right)$$
if $h_{wt} > h_{tile}$ (3)

where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm), h_{wt} is the water table height above the impermeable layer (mm), h_{tile} is the tile height above the impermeable layer (mm), and t_{drain} is the time required to drain the soil to field capacity (h).

AERATION STRESS

When soil water content approaches saturation, plants may suffer from aeration stress. The water content of the root zone is considered in estimating the degree of stress (Williams et al., 1984).

$$SAT = 100 \left(\frac{SW_{rz}}{POR} - CAF \right) / (1 - CAF) \tag{4}$$

$$AS = 1. - \frac{SAT}{SAT + \exp(5.10 - 0.082SAT)}$$

$$SAT > 0.0$$
 (5)

where SAT is the saturation factor, SW_{rz} is the water content of the root zone (mm), POR is the porosity of the root zone (mm), CAF is the critical aeration factor (0.85 was used for corn and soybeans in this study), and AS is the aeration stress factor. Actual plant water uptake is limited by multiplying aeration stress by potential water uptake. Actual plant stress is determined as the minimum stress of aeration, limiting water, temperature, nitrogen, and phosphorus stresses.

LANDSCAPES WITH POTHOLES AND SURFACE INLETS

Many areas of the Midwest were formed on young glacial till plains that contain numerous closed depressions or potholes. These potholes often fill with water, especially after snowmelt and heavy spring rains (Hatfield et al., 1999). The potholes have a significant effect on stream flow and the hydrologic balance, and can also reduce crop yields when they fill with water. Water balance for a pothole is given as:

$$V = V_{pcp} + V_{flowin} + V_{stored}$$
$$- V_{evap} - V_{seep} - V_{flowout}$$
 (6)

where V is the volume of water in the impoundment at the end of the day (m^3) , V_{pcp} is the volume of precipitation falling on the water body during the day (m^3) , V_{flowin} is surface runoff and lateral soil flow from upland HRUs in the subbasin during the day (m^3) , V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3) , V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3) , V_{seep} is the volume of water lost from the water body by seepage (m^3) , and $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3) . The user specifies the fraction of flow from upland HRUs that contributes to the pothole HRU, with the remainder flowing

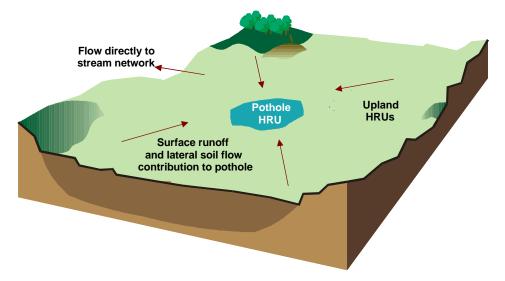


Figure 2. Location of pothole and upland hydrologic response units (HRUs) in the landscape.

directly into the channel system (fig. 2). Previous SWAT simulations have assumed that all HRU flow contributes directly to the channel system without interacting with other HRUs.

The volume of precipitation falling on the pothole during a given day is given as:

$$V_{pcp} = 10 * R_{day} * SA \tag{7}$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m³), R_{day} is the amount of precipitation falling on a given day (mm), and SA is the surface area of the water body (ha). The surface area varies with change in the volume of water stored in the impoundment. Based on field observations, most potholes in the Walnut Creek watershed are cone-shaped. Therefore, for surface area calculations, the pothole is assumed to be cone-shaped. The surface area is updated daily using the equation:

$$SA = \frac{\pi}{10^4} * \left(\frac{3V}{\pi * slp}\right)^{2/3}$$
 (8)

where SA is the surface area of the water body (ha), V is the volume of water in the impoundment (m³), and slp is the slope of the HRU (m m⁻¹).

Water entering the pothole on a given day may be contributed from any HRU in the subbasin. The inflow to the pothole is calculated:

$$V_{flowin} =$$
 (9)

$$\sum_{HRU=1}^{n} \left[pot_{-} fr * 10 * (Q_{surf_{,}HRU} + Q_{lat_{,}HRU}) * area_{HRU} \right]$$

where V_{flowin} is the volume of water flowing into the pothole on a given day (m³), n is the number of HRUs contributing water to the pothole, pot_fr is the fraction of the HRU area draining into the pothole, $Q_{surf,HRU}$ is the surface runoff from the HRU on a given day (mm), $Q_{lat,HRU}$ is the lateral flow generated in the HRU on a given day (mm), and $area_{HRU}$ is the HRU area (ha).

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 * \left(1 - \frac{LAI}{LAI_{evap}}\right) * E_o * SA$$
if $LAI < LAI_{evap}$ (10)

$$V_{evap} = 0 \text{ if } LAI \ge LAI_{evap}$$
 (11)

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m³), LAI is the leaf area index of the plants growing in the pothole, LAI_{evap} is the leaf area index at which no evaporation occurs from the water surface, E_o is the potential evapotranspiration for a given day (mm), and SA is the surface area of the water body (ha).

If flooding and plant die-off occur and the pothole stays too wet to replant during the crop growing season, the pothole will lay fallow for the rest of the year. Thus, evaporation from the pothole will be calculated from either ponding water or bare soil.

The volume of water lost by infiltration from the pothole into the soil on a given day is calculated as a function of the water content of the soil profile beneath the pothole:

$$V_{seep} = 240 * K_{sat} * SA$$
if $SW < 0.5 * FC$ (12)

$$V_{seep} = 240 * \left(1 - \frac{SW}{FC}\right) * K_{sat} * SA$$
if $0.5 * FC \le SW < FC$ (13)

$$V_{seep} = 0 \text{ if } SW \ge FC \tag{14}$$

where V_{seep} is the volume of water lost from the water body by infiltration into the soil (m³), K_{sat} is the effective saturated hydraulic conductivity of the soil (mm h⁻¹), SA is the surface area of the water body (ha), SW is the soil water content of the profile on a given day (mm), and FC is the field capacity soil water content (mm). Water lost from the pothole by seepage is added to the soil profile. If the soil profile is saturated, infiltration does not occur.

Water may be removed from the pothole in two different types of outflow. When the volume of water in the pothole exceeds the maximum storage, the excess water is assumed to overflow and enter ditches or streams. The other type of flow from the pothole is via surface inlet drains connected to tile underlying the pothole.

Pothole outflow caused by overflow is calculated:

$$V_{flowout} = V - V_{pot,mx}$$
if $V > V_{pot,mx}$ (15)

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m³), V is the volume of water stored in the pothole at the end of the day (m³), and $V_{pot,mx}$ is the maximum amount of water that can be stored in the pothole (m³).

When tile surface inlets are installed in a pothole, the pothole will contribute water to channels through tile flow. The pothole outflow originating from surface inlets is:

$$V_{flowout} = q_{tile} \times 86400$$
 if $V > q_{tile} * 86400$ (16)

$$V_{flowout} = V \text{ if } V \le q_{tile} * 86400 \tag{17}$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m³), q_{tile} is the average daily tile flow rate (m³ s⁻¹), and V is the volume of water stored in the pothole (m³).

When overflow and surface inlet-led flow in a pothole occur at the same time, the pothole outflow is:

$$V_{flowout} = q_{tile} *86400 + V - V_{pot,mx}$$
 (18)

SWAT INPUT VARIABLES FOR TILES AND POTHOLES

In addition to the basic model inputs (topography, soils, land use, and weather), the following variables are input by users to SWAT to simulate tile flow and potholes:

- Depth to subsurface tile (d_{drain} , mm).
- Time to drain soil to field capacity (t_{drain}, h), the time required to drain the water table to the tile depth.
- Drain tile lag time (g_{drain} , h), the amount of time between the transfer of water from the soil to the drain tile and the release of the water from the drain tile outlet to the channel.
- Fraction of HRU area that drains into the pothole (not fr).
- Average daily flow rate of surface inlet (pot_tile, m³ s⁻¹)
- Maximum volume of water stored in the pothole (pot_volmx, 10⁴ m³).
- Initial volume of water stored in the pothole (10⁴ m³).

- Equilibrium sediment concentration in pothole (mg L⁻¹), generally from 500 to 1000 ppm.
- Nitrate decay rate in pothole (1/day).

MODEL EVALUATION

WATERSHED DESCRIPTION

The 5130 ha Walnut Creek watershed (WCW), located in Story and Boone counties in central Iowa, is typical of the poorly drained, gently rolling landscapes of the Des Moines lobe landscape of central Iowa and southern Minnesota (Andrews and Dideriksen, 1981). This landscape was formed on a young till plane and contains numerous closed depressions or potholes as a result of a poorly developed, geologically young surface drainage network. These potholes often retain water for extended periods, especially during snowmelt and after heavy rainfall, which can result in a reduction in crop yields. The upland soils are underlain by a dense unoxidized till that restricts vertical drainage, resulting in poorly drained soils in lower elevation areas. A corn-soybean rotation cropping system is predominately used in this area.

The watershed has an average elevation of about 300 m above sea level. The average annual precipitation during the eight years used to evaluate this model was approximately 820 mm, and the average temperature during crop growth seasons ranged from 9.0°C to 23.0°C. These beneficial weather conditions along with fertile soils result in high corn and soybean yields.

SENSITIVITY ANALYSIS

The sensitivity of six parameters related to the tile drain functions of SWAT (d_{drain} , t_{drain} , g_{drain} , pot_fr , pot_tile , and pot_volmx) were analyzed in order to understand their influence on model predictions. As model sensitivity to each variable was determined, the other variables were held constant at the typical values listed in table 1. The impacts of tile and pothole parameters on daily and monthly subsurface flows were investigated using the Nash-Sutcliffe E values (Nash and Sutcliffe, 1970) and the mean absolute errors (MAE). E value is calculated as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{mi} - X_{pi})^{2}}{\sum_{i=1}^{n} (X_{mi} - \overline{X}_{m})^{2}}$$
(19)

where E is the efficiency (goodness of fit) of the model, and \overline{X}_m is the average measured values. A value of E = 1.0 indicates that the pattern of model prediction perfectly matches the measured data.

Table 1. Parameters used in sensitivity analysis.

Parameter	Description	Typical Value	Range
d_{drain}	Depth to surface drain (mm)	1200	50 to 1450
t_{drain}	Time to drain soil to field capacity (h)	52	2 to 94
8drain	Drain tile lag time (h)	25	
pot_fr	Fraction of HRU area that drains into pothole	0.7	0.1 to 1.0
pot_tile	Average daily outflow to main channel from tile flow (m ³ s ⁻¹)	3	
pot_volx	Maximum volume of water stored in the pothole (10 ⁴ m ³)	600	

$$MAE = \frac{\sum_{i=1}^{n} \left| X_{mi} - X_{pi} \right|}{n}$$
 (20)

where X_{mi} is the measured values, X_{pi} is the predicted values, and n is the number of predicted/measured values. A value of MAE = 0 indicates that the model prediction perfectly matches the measured data.

Site 210 was dominated with tile drains and had no interflow from other subbasins, so it was selected for the sensitivity analysis.

DATA MEASUREMENT

Weather and stream flows have been intensively monitored at a number of sites within the watershed since 1992 by the USDA-ARS National Soil Tilth Laboratory (Hatfield et al., 1999). Stream flows were calculated from water stage and frequently updated rating curves. Water quality samples (1 L) were collected at each site once a week when flow occurred, with additional samples collected during flow events. A more detailed description of hydrologic data measurements for WCW can be found in Jaynes et al. (1999).

Precipitation data measured by 17 rain gauges within the watershed (fig. 3) were used in SWAT. The maximum and minimum temperature data sets were measured every day at two locations within the watershed. Solar radiation data were measured daily at one station. Daily streamflow data from the outlet of the watershed (site 330) and the middle of the watershed (site 310) were utilized over a period of record from 1992 to 1999. In addition, daily discharge data from 1992 to 1999 for site 210 were used, where site 210 is the outlet of a large drainage district drain and is influenced primarily by subsurface drainage. The monthly discharges were computed by summing the daily values. Both daily and monthly values were used to assess the performance of the original and enhanced versions of SWAT.

INPUT DATA AND MODEL ASSUMPTIONS

Maps of digital elevation, land use, and soils, and measured daily precipitation, temperature, and solar radiation for the watershed were provided during the initial setup of the input data files for SWAT using the ArcView interface for SWAT2000 (AVSWAT). Other input data, such as daily wind speed and relative humidity, were generated by SWAT from long-term monthly statistics. The Penman-Monteith

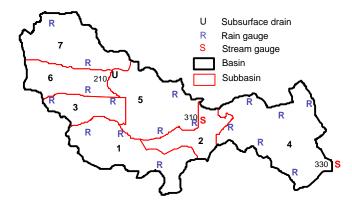


Figure 3. Subbasins (1-7), sites (210, 310, and 330), and measurement gauges in WCW used by SWAT.

Table 2. Soils, land use, tiles, and potholes used in SWAT.

Percent	
of Area	Soil Types
18.0	Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls)
30.0	Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls)
6.1	Harps (fine-loamy, mixed, superactive, mesic Typic Calciaquolls)
3.6	Okoboji (fine, smectitic, mesic Cumulic Vertic Endoaquolls)
14.0	Nicollet (fine-loamy, mixed, superactive, mesic, Aquic Hapludolls)
18.7	Webster (fine-loamy, mixed, superactive, mesic, Typic Haplaquolls)
9.6	Lester (fine-loamy, mixed, superactive, mesic Mollic Hapludalfs)
	Land use, tile, and pothole areas
66.3	Total area with tiles
57.4	Area of total runoff flowing to potholes
9.7	Total potholes area
87.0	Total farm land
14.7	Continuous corn area of farm land
85.3	Corn-soybean area of farm land
13.0	Total forest and other lands

method within SWAT was selected for calculation of potential evapotranspiration (ET).

Corn and soybean occupied 87% of the total area, while other crops, roads, and forest occupied 13% of the area (table 2). Continuous corn production occurred on 15% of the total farmland, while 85% of the tilled area was in a corn-soybean rotation (Hatfield et al., 1999).

The seven predominant soils within the watershed were included in the model (table 2). The very poorly drained Okoboji and Harps soils were assigned as potholes. Based on figure 4 and Hatfield et al. (1999), we estimated that about 75% of the total watershed area was tile drained and that 57% of the total surface runoff directly flowed into potholes. Pothole area occupied 9.7% of the watershed. Table 2 summarizes the percent land use, soils, tiles, and potholes used by SWAT.

A standard tile drain depth of 1.2 m was used in this study. The initial number of soil layers in soil files created from the State Soil Geographic (STATSGO) soils data for WCW varied from 3 to 4, and the distribution of layer depths of soils varied. To set up tile drains at a depth of 1.2 m, the number of soil layers was modified to 7 for all soils. Tile drains are

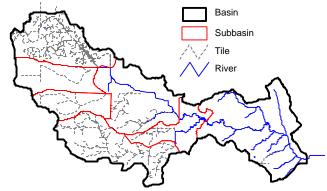


Figure 4. Distributions of subsurface drains and streams across WCW.

usually designed to reduce the water content to field capacity within 48 h, so the initial value of tile drain parameter, t_{drain} (time to drain soil to field capacity), was set at 48 h, which was calibrated later.

An average daily outflow to the main channel from pothole via the tile (pot_tile) of 3.0 m³ d⁻¹ and a maximum volume of water stored in the pothole (pot_volx) of 600×10^4 m³ were assumed.

MODEL EVALUATION AND CALIBRATION METHODS

The Nash-Sutcliffe model efficiency (*E*) and relative mean error (RME) were respectively used to compare the pattern and magnitude of the model output values to those of measured values. The RME is calculated as follows:

$$RME = \frac{\sum_{i=1}^{n} (X_{mi} - X_{pi})}{\sum_{i=1}^{n} (X_{mi})}$$
 (21)

A value of RME = 0 indicates the predicted total amount of flow or loads equals the measured value. For the purpose of comparison, the same input data were used for both SWAT-M and SWAT2000.

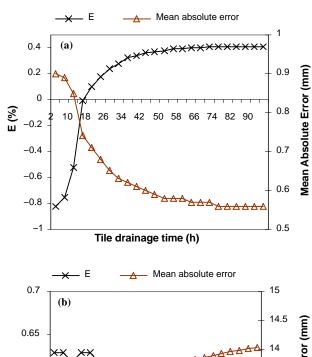
Both versions of SWAT were calibrated for the period of 1992 to 1995 and validated for the period of 1996 to 1999. Typically, there are two mainly adjustable parameters used for the calibration of surface runoff in stream flow in SWAT (Arnold et al., 1999). These parameters are esco (a soil evaporation compensation coefficient) and cn2 (condition II runoff curve number) for the ET and runoff calibration. The main groundwater parameters describing water movement, such as gwqmn (threshold depth of water in the shallow aquifer required for return flow to occur), gw_revap (the coefficient of groundwater moving to an adjacent unsaturated zone), revapmn (threshold depth of water in the shallow aquifer for groundwater moving to an adjacent unsaturated zone to occur), and alpha_bf (baseflow alpha factor), were used when baseflow or total water balance deviated from the measured values. The other calibrated parameter used in this study was surlag (surface runoff lag time) for daily flow or flow peak calibration. Because of the added complexity of simulating a watershed with tile drainage and pothole surface storage, additional parameters such as t_{drain} and g_{drain} (drain tile lag time) needed to be included for flow calibration.

RESULTS AND DISCUSSION

Among the major six tile and pothole related parameters, pot_tile , pot_volmx , and g_{drain} were not sensitive to the subsurface flow of the selected subbasin in WCW. The sensitivity of the other three parameters is analyzed below.

Sensitivity of Tile Drain Time (t_{drain})

Figure 5a illustrates the sensitivity of t_{drain} on daily subsurface flow. The t_{drain} variable was varied from 2 to 94 h. Both E (-0.8 to 0.4) and MAE (0.56 to 0.9) varied greatly, indicating that daily subsurface flow was sensitive to t_{drain} . Values of E increased greatly as t_{drain} increased from 2 to 42 h, and then leveled off as t_{drain} increased. Therefore, the optimum t_{drain} to maximize daily flow E and minimize MAE was in the range of 24 to 94 h.



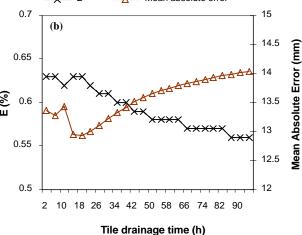
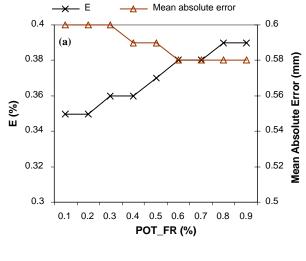


Figure 5. Effects (E and MAE values) of the tile drainage time (t_{drain}) on (a) daily and (b) monthly subsurface flows at WCW site 210.

The sensitivity of t_{drain} on monthly subsurface flow differed from the daily subsurface flow (fig. 5b). Overall, monthly subsurface flow illustrated less sensitivity to t_{drain} since both E and MAE illustrated less variation (E = 0.56 to 0.63, MAE = 12.93 to 14.0). When t_{drain} varied from 2 to 42 h, the E value remained at or above 0.6, and the simulated monthly subsurface flow was near measured values. Nevertheless, E continuously decreased and MAE continuously increased as t_{drain} increased above 42 h. Very low t_{drain} values caused daily peaks to exceed measured peaks, lowering daily E values. As t_{drain} increased, total subsurface flow decreased, resulting in lower monthly E values. Therefore, the effect of t_{drain} on both daily and monthly flow simulations should be considered when setting the input value. The daily and monthly E values of flow may have responded differently to various parameters because the number of the samples was different and the predicted daily and monthly flows were different in timing when compared to the measured values.

Sensitivity of Fraction of HRU Area Draining into the Pothole (pot_fr)

Figures 6a and 6b illustrate the effect of pot_fr on daily and monthly subsurface flows, respectively. Unlike t_{drain} ,



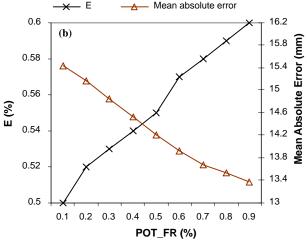
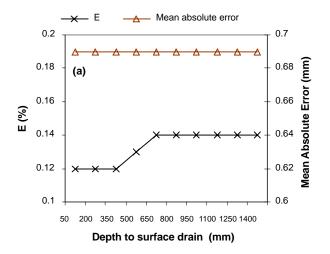


Figure 6. Effects (*E* and MAE values) of the fraction of the area that drains into potholes (*pot_fr*) on (a) daily and (b) monthly subsurface flows at WCW site 210.

pot_fr had a larger impact on the monthly subsurface flow than on the daily. For both daily and monthly subsurface flows, E increased and MAE decreased as pot_fr increased. Increasing pot_fr forces more water into potholes with less flowing directly into channels, lowering daily and monthly flows and increasing E values.

Sensitivity of Depth to Subsurface Tile (d_{drain})

Figures 7a and 7b illustrate that E for the daily and the monthly subsurface flows increased when d_{drain} was changed from 50 to 1450 mm, indicating a slight improvement in subsurface flow prediction as tile depth increased. Increasing d_{drain} (lowering the tile depth) increased simulated flow, causing improvements in E values. Little improvement was obtained for subsurface flow simulation after d_{drain} exceeded 650 mm depth. Additionally, the simulation of the monthly subsurface flow showed slightly more improvement than daily flow as d_{drain} was increased. A validation of d_{drain} sensitivity needs to be determined on field plots where the impact of drain depth on tile flow has been measured. There was also interaction between the tile and pothole parameters, and the combined sensitivity should also be examined.



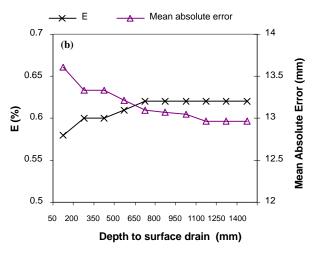


Figure 7. Effects (E and MAE values) of the depth to subsurface drain tiles (d_{drain}) on (a) daily and (b) monthly subsurface flows at WCW site 210.

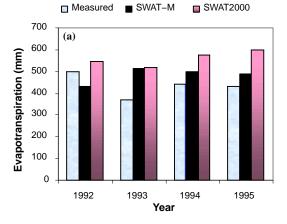
WATER BALANCE

Initial calibrations of SWAT were performed based on the measured annual ET and stream discharge data at the outlet of WCW from 1992 to 1995 (Hatfield et al., 1999) (fig. 8). The annual average stream discharge (284.1 mm) at the outlet of WCW and annual average ET (483.7 mm) simulated by SWAT-M for the period of 1992 to 1995 were much closer to measured values (345.8 and 435.0 mm, respectively) than that of SWAT2000 (191.0 and 560.1 mm).

Figure 8 demonstrates that enhancement of the hydrology routine within SWAT-M resulted in better prediction of annual stream discharge and ET compared to SWAT2000. A substantial change in the water balance components of surface runoff, groundwater flow, and tile flow was found in the outputs of SWAT-M (table 3). Similar to field measurements, more tile and groundwater flows along with less surface runoff were simulated by SWAT-M than by SWAT2000.

MONTHLY STREAMFLOW SIMULATION AT WCW SITES 310 AND 330

The results of measured and simulated monthly flow at site 310 are summarized in table 4. *E* values of 0.88 and 0.82 for the calibration and validation periods, respectively,



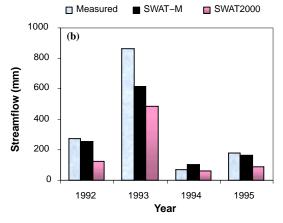


Figure 8. Simulated and measured annual ET values and streamflows of WCW.

indicate that the patterns of the predicted flows at site 310 reasonably matched those of the measured flow values. After the level of predicted flow was calibrated within –2% of the measured values (table 4), –1% flow prediction error during the validation period, which suggests that SWAT accurately predicted the amount of flow at site 310. Compared to SWAT-M, SWAT2000 predicted both patterns and amounts of flows at site 310 with much larger errors (*E* values of 0.36 and 0.13 for the calibration and validation periods, respectively; RME values of –67% and –78%). Figures 9a and 9b illustrate that patterns of the monthly flows at site 310 were predicted by SWAT-M much better than by SWAT2000.

Figures 10a and 10b and table 5 represent measured and simulated monthly stream flows at site 330 during the calibration and validation periods. It is apparent from these

Table 3. Comparisons of water components of SWAT-M and SWAT2000 for WCW (all values in mm).

	Surface	Runoff	Runoff Groundwater Flow			Tile Flow		
Year	SWAT SWAT M 2000		SWAT M	SWAT 2000	SWAT M	SWAT 2000		
1992	80.2	95.3	84.5	12.3	84.5	16.5		
1993	161.5	298.3	259.7	116.8	194.2	70.4		
1994	45.4	54.4	24.0	4.4	30.9	3.2		
1995	53.2	64.5	56.0	13.9	56.5	9.3		
Avg.	85.1	128.1	106.0	36.9	91.5	24.9		

figures and the E values (table 5) that the patterns of monthly flows at site 330 simulated by SWAT-M during the calibration (E = 0.84) and validation (E = 0.72) periods were fairly close to those of the measured data. However, SWAT-M underestimated the flows as a result of the extremely heavy rainfall during July 1993. This resulted in a -18% RME at site 330 during the calibration period. The flow prediction error was 10% during the validation period. In comparison to SWAT-M, SWAT2000 underestimated the flows in most months at site 330 (fig. 10a and 10b) and achieved lower E values (0.72 and 0.56 for calibration and validation, respectively). The average monthly flows simulated by SWAT-M at site 330 were closer to the measured values, as compared to those simulated by SWAT2000 (RME = -33% and -51% for calibration and validation, respectively). As summarized from the above discussion for both sites 310 and 330 and from figures 9a, 9b, 10a, and 10b, it is reasonable to conclude that SWAT-M predicted monthly flow of WCW fairly well.

DAILY STREAMFLOW AT WCW SITES 310 AND 330

SWAT-M was generally able to simulate daily flows most of the time, as illustrated in figures 9c, 9d, 10c, and 10d, but it underpredicted the high peak flows occurring at both sites 310 and 330 on 9 July 1993, when 75 mm precipitation occurred. This is probably due to the fact that SWAT simulates short-duration, high flow rate events based on theoretical rating curves rather than measured rating curves, or that daily time-based simulations are of less accuracy in predicting flow under this extreme event. At both sites 310 and 330, daily flows occurring on 7 March 1993, 10 February 1996, and 18 February 1997 were also not predicted well by SWAT-M. By examining the daily data, we found that the temperatures were below 0°C before and after these days, but above 0°C on these days, which caused snowmelt. In addition, the large rainfall events before these days coincided with the temperature warming well above freezing. Therefore, it can reasonably be assumed that flows during these

Table 4. Values of E, RME, mean, and SD for daily and monthly flows of 1992-1999 at WCW site 310.

		Daily Flow					Mont	hly Flow	
	-	E ^[a]	RME ^[b] (%)	Mean (mm day ⁻¹)	SD ^[c]	E	RME (%)	Mean (mm month ⁻¹)	SD
Calibration	Measured			0.91	1.97			27.73	43.95
	SWAT-M	0.55	-2	0.89	1.83	0.88	-2	27.15	35.53
	SWAT2000	0.39	-67	0.29	0.85	0.36	-67	8.87	15.26
Validation	Measured			0.66	1.44			20.01	29.45
	SWAT-M	0.49	-1	0.65	1.45	0.82	-1	19.77	22.98
	SWAT2000	0.35	-79	0.14	0.58	0.13	-78	4.45	7.56

[[]a] Nash-Sutcliffe model efficiency.

[[]b] Relative mean error.

[[]c] Standard deviation.

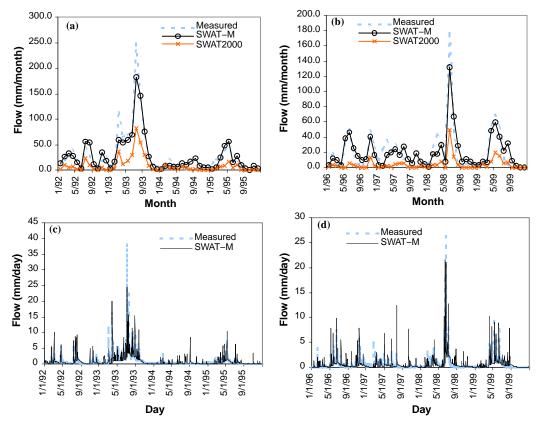


Figure 9. Simulated and measured monthly (a and b) and daily (c and d) flows at WCW site 310 for the calibration (a and c) and validation (b and d) time periods.

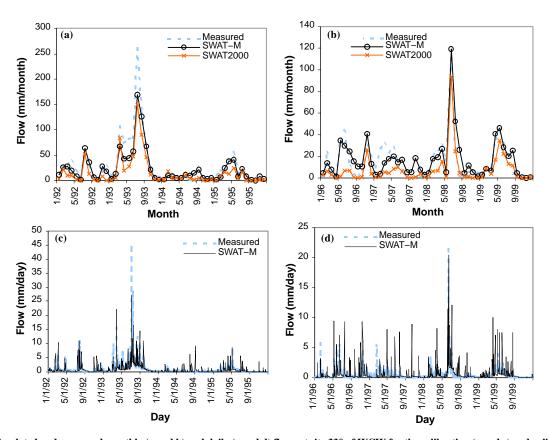


Figure 10. Simulated and measured monthly (a and b) and daily (c and d) flows at site 330 of WCW for the calibration (a and c) and validation (b and d) time periods.

Table 5. Values of E, RME, mean, and SD for daily and monthly flows of 1992-1999 at site 330 of Walnut Creek.

			Daily Flow				Monthly Flow			
		$E^{[a]}$	RME ^[b] (%)	Mean (mm day ⁻¹)	SD ^[c]	E	RME (%)	Mean (mm month ⁻¹)	SD	
Calibration	Measured			0.95	2.18			28.80	45.56	
	SWAT-M	0.51	-18	0.78	1.79	0.84	-18	23.61	32.27	
	SWAT2000	0.47	-33	0.52	1.72	0.72	-33	15.86	28.10	
Validation	Measured			0.51	1.01			15.46	19.13	
	SWAT-M	-0.11	10	0.56	1.40	0.72	10	17.05	19.71	
	SWAT2000	0.32	-54	0.26	1.15	0.56	-51	8.31	13.83	

[[]a] Nash-Sutcliffe model efficiency.

days were probably a combination of increased flow rate and ice damming at the data station, which could have raised the stream level behind the weir and resulted in false high-flow readings.

SWAT-M simulated the patterns of daily flows less accurately (lower E values of 0.55/0.49 and 0.51/-0.11 during the calibration/validation periods for sites 310 and 330, respectively) compared to the monthly results (tables 4 and 5). Nevertheless, SWAT-M reached better daily flow E values than SWAT2000 (E=0.39/0.35 for calibration/validation) at site 310. At site 330, SWAT-M had a better E value in calibration but a worse E value in validation than SWAT2000. Overall, in terms of both pattern and amount of flow (tables 4 and 5), SWAT-M improved in daily flow prediction based on SWAT2000.

SUBSURFACE FLOW SIMULATION AT WCW SITE 210

Both figures 11a and 11b and the *E* values (0.61 and 0.70 for the simulated monthly subsurface flows at site 210 during the calibration and validation periods, respectively) listed in table 6 demonstrate that SWAT-M predicted the patterns of simulated monthly subsurface flow relatively well. RME values for the predicted monthly flow were 10% and –9% during the calibration and validation periods, respectively, indicating that the amount of the predicted monthly flows by SWAT-M was close to that of the measured values. In contrast, as illustrated in figures 11a and 11b and table 6, SWAT2000 predicted the patterns of monthly subsurface flows with much less accuracy (*E* values of –0.33 and –0.42 for calibration and validation, respectively), and the amounts of predicted subsurface flows (RME values of –93% and

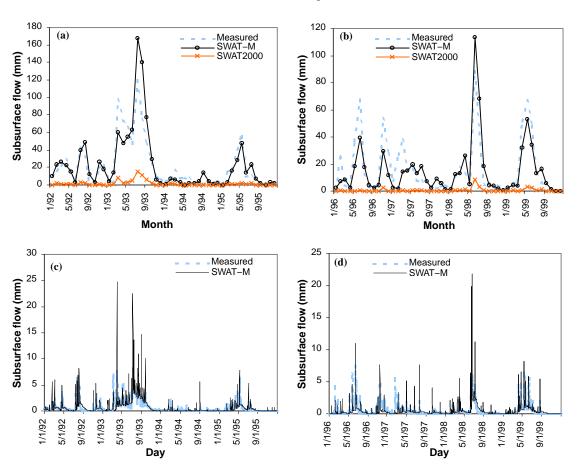


Figure 11. Simulated and measured monthly (a and b) and daily (c and d) flows at WCW site 210 for the calibration (a and c) and validation (b and d) time periods.

[[]b] Relative mean error.

[[]c] Standard deviation.

Table 6. Values of E, RME, mean, and SD for daily and monthly flows of 1992-1999 at WCW site 210.

			Daily Flow				Mont	hly Flow	
		$E^{[a]}$	RME ^[b] (%)	Mean (mm day ⁻¹)	SD ^[c]	E	RME (%)	Mean (mm month ⁻¹)	SD
Calibration	Measured			0.69	1.12			20.96	27.43
	SWAT-M	-0.23	10	0.76	1.68	0.67	10	23.13	33.84
	SWAT2000	-0.15	-93	0.05	0.17	-0.33	-93	1.64	3.02
Validation	Measured			0.52	1.00			15.91	21.30
	SWAT-M	-0.12	-9	0.48	1.25	0.70	-9	14.56	20.22
	SWAT2000	-0.16	-95	0.02	0.11	-0.42	-93	1.02	1.73

[[]a] Nash-Sutcliffe model efficiency.

-95% for calibration and validation, respectively) were much lower than the measured values.

For the daily simulation, as shown in figures 11c and 11d and listed in table 6, SWAT-M did not predict subsurface flows on some days of the simulation period at this site, which resulted in a great discrepancy between the pattern of the predicted daily subsurface flow (E values = -0.23 for calibration and -0.12 for validation) and that of the measured data

The ranges of adjusted parameters suggested by the SWAT model and the calibrated values of the adjusted parameters used for flow calibration of the model for WCW are listed in table 7.

SUMMARY AND CONCLUSIONS

In this study, the SWAT (version 2000) model was modified to simulate water table dynamics and linked with a simple tile flow equation. Algorithms were also added to SWAT to include simulation of potholes (closed depressions), surface tile inlets, and aeration plant stress. The water table routines provided a more realistic simulation of tile flow with increasing tile depth. The new routines illustrate an increase in tile flow as tile depth increases. The new tile flow equation uses a design drawdown time (input by the user) to simulate daily flow volumes as a function of water table height above the tiles. We are assuming that the tile systems have already been designed (with a certain spacing, tile size, etc.), and we are attempting to simulate the environmental impact of the tile system at the watershed scale. The design drawdown approach has the advantage of being easy to parameterize on large basins. A sensitivity analysis of several new tile and pothole parameters was performed on a subarea (site 210) of the Walnut Creek watershed (WCW) in central Iowa, where mostly subsurface flow occurred.

The SWAT-M was evaluated at a watershed scale using over eight years of measured flow data from WCW. At the

same time, comparisons between SWAT-M and SWAT2000 were conducted. A stream location near the center of WCW (site 310) and at the outlet (site 330) were selected to investigate overall performance of both versions of the SWAT model, while site 210 was used to scrutinize SWAT-M's capability of simulating subsurface flow. The initial calibrations of the models were carried out based on the measured annual ET and stream discharge of WCW. The annually averaged stream discharge at the outlet of WCW and annually averaged ET simulated by SWAT-M for the period of 1992 to 1995 were close to measured values. As illustrated by both figures and E values for the simulated monthly flows (0.88/0.82 and 0.84/0.72 for calibration/validation at sites 310 and 330, respectively), SWAT-M reasonably well predicted the pattern of monthly flow in the gently rolling landscape of WCW where tile drains and potholes are common. The relative mean errors for the amounts of the predicted monthly flows were -2% and -1%during the calibration and validation periods, respectively, at site 310, and -18% and 10% at site 330. Both pattern and amount of the monthly flow were predicted much better by SWAT-M than by SWAT2000.

However, compared to the monthly results, daily flows predicted by SWAT-M were less accurate (*E* values of 0.55/0.49 and 0.51/–0.11 during the calibration/validation periods for sites 310 and 330, respectively).

By investigating site 210, it was concluded that both the pattern and magnitude of the simulated monthly subsurface flows were fairly close to the measured ones. Nevertheless, SWAT-M's simulation of daily subsurface flow was not as good as the monthly result. In comparing SWAT-M to SWAT2000, the former generally estimated daily flows better than the latter in terms of pattern and amount.

The modifications to SWAT presented in this study have being incorporated into SWAT2003. Although the SWAT model has been greatly enhanced based on its old version (SWAT2000), and predicted monthly results were considered in agreement with measured values, the model's tile drain

Table 7. Calibrated values of adjusted parameters for flow calibration of the model for WCW.

Parameter	Description	Range	Calibrated Value
esco	Soil evaporation compensation factor	0.2 to 1.0	0.97 to 1.0
cn2	Initial SCS runoff curve number to moisture condition II	30 to 100	60 to 78
gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)		46.7 to 65.7
gw_revap	Coefficient of groundwater moving to an adjacent unsaturated zone	0.02 to 0.2	0.2
revapmn	Threshold depth of water in the shallow aquifer required for "revap" to occur (mm)		45 to 49
alpha_bf	Baseflow alpha factor (days)	0.0 to 1.0	0.48 to 0.91
surlag	Surface runoff lag coefficient	1 to 12	1.115
t_{drain}	Time to drain soil to field capacity (h)		34.31 to 44.31

[[]b] Relative mean error.

[[]c] Standard deviation.

and pothole components need further improvement in order to obtain a higher accuracy in predicting flow of watersheds with tile drains and potholes. Finally, it would be desirable to develop GIS tools to determine several of the pothole parameters required by the model.

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